Magnet Specifications for AC Dipole Options in the Mu2e Experiment

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Abstract

This note presents preliminary specifications for magnet design in several possible configurations of AC dipoles which have been proposed for the extinction system in the Mu2e experiment. General optimization of the design drives us to long, low field magnets in regions of high β in the bend plane, and we have used $\beta = 250$ m and a 6 m total length for all designs considered.

1 Introduction

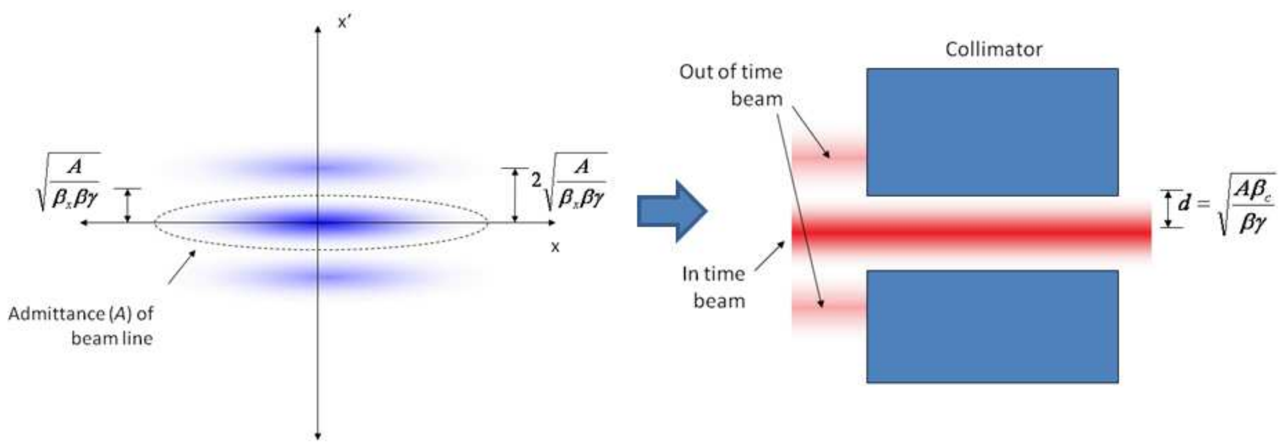

Figure 1: Effect of the AC dipole field in phase space. Beam line admittance A is indicated by the ellipse. Shown at right is effect of the dipole at the collimator (or other defining aperture).

Elsewhere[1], we have discussed the relationship between requirements of an AC dipole and the local beam line parameters in the context of a single harmonic system operating at half the bunch

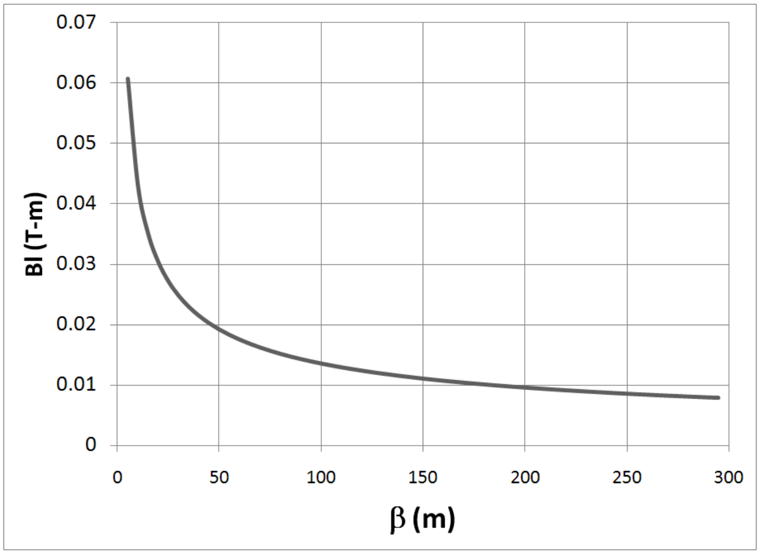

Figure 2: The minimum integrated bend field required for complete extinction as a function of β_x, assuming an admittance of 50 π-mm-mr. Note that depending on the required waveform, the actual peak integrated field may be significantly higher.

rate. We present a generalized and simplified version of that argument here. Throughout, we will assume a kinetic energy of 8 GeV and a normalized beam admittance of 50 π-mm-mr.

The effect of the AC dipole/collimator system can be represented as a translation in transverse phase space, as illustrated in Figure 1. In general, out of time beam may be present anywhere within the admittance of the beam line, so complete extinction is not assured until a deflection amplitude of

$$\Delta\theta = 2\sqrt{\frac{A}{\beta_x \beta\gamma}} \tag{1}$$

is achieved, where β_x is the betatron function in the bend plane and β and γ have their usual definitions. We will therefore use this as our definition of the amplitude for complete extinction. The required integrated field achieve extinction is then

$$Bl = 2(B\rho)\sqrt{\frac{A}{\beta_x \beta\gamma}} \tag{2}$$

as plotted in Figure 2 for the nominal Mu2e beam line parameters.

Generally speaking, magnet and power supply complexity increases with stored energy

$$U \propto B^2 Lwg = ((Bl)^2/L)wg \tag{3}$$

Here, w is the aperture in the bend plane, which is proportional to $\sqrt{\beta_x}$. The gap g is the minimum aperture in the non-bend plane through which the beam can pass. Ignoring chromatic effects, this is proportional to $\sqrt{L}$, so we have

$$U \propto \frac{1}{\sqrt{L\beta_x}} \tag{4}$$

Thus, regardless of the details of the AC dipole design, we are driven toward the highest values of β_x and the longest magnets which can be accommodated in the beam line. Preliminary analysis has indicated that the Mu2e beam line should be able to accommodate a β_x value up to about 250 m and a total length of 6 m[2], so we will adopt these are our working points. Note that this reduces the stored energy by a factor of almost four relative to our preliminary specifications of β_x=50 m and L=6 m; however, because of the weak dependence of Eq. 4 on these parameters, significant further improvement would be difficult.

2 Pulse Shape (Harmonic Content)

In addition to the total field requirement, one must consider the transmission efficiency of the in time beam, and this is a particular concern for the single harmonic design in the Mu2e proposal. This issue was analyzed in detail in [3]. Several schemes were considered, as illustrated in Figure 3:

- **Sine Wave:** A sine wave running at half the bunch rate, as described in the Mu2e proposal[4].
- **Modified Sine Wave A:** The same sine wave modified by a sine wave with the opposite polarity, 1/17 the amplitude, and 17 times the frequency (5.1 MHz), to reduce the beam slewing to exactly zero at the nominal bunch time.
- **Modified Sine Wave B:** The configuration described above, but with the higher harmonic having 2/17 the amplitude of the primary to expand the transmission window somewhat further.
- **MECO:** The configuration proposed for MECO[5], comprised of magnets operating at the first three harmonics of the bunch frequency, with relative amplitudes of 1:.74:.63, to approximate a short square pulse.

In all cases, the amplitude was normalized to give complete extinction at ±100 ns, according to Eq. 1. The transmission results are shown in Figure 4. As can be seen, the single dipole scheme in the proposal has significant beam loss problems for bunch lengths longer than $\sigma_t \approx 10$ ns.

The "MECO" scheme is superior in this regard, as is "Modified Sine Wave A". "Modified Sine Wave B" has the longest full transmission window, but can suffer inefficiencies for larger beam emittances due to beam scraping against the opposite wall of the collimator.

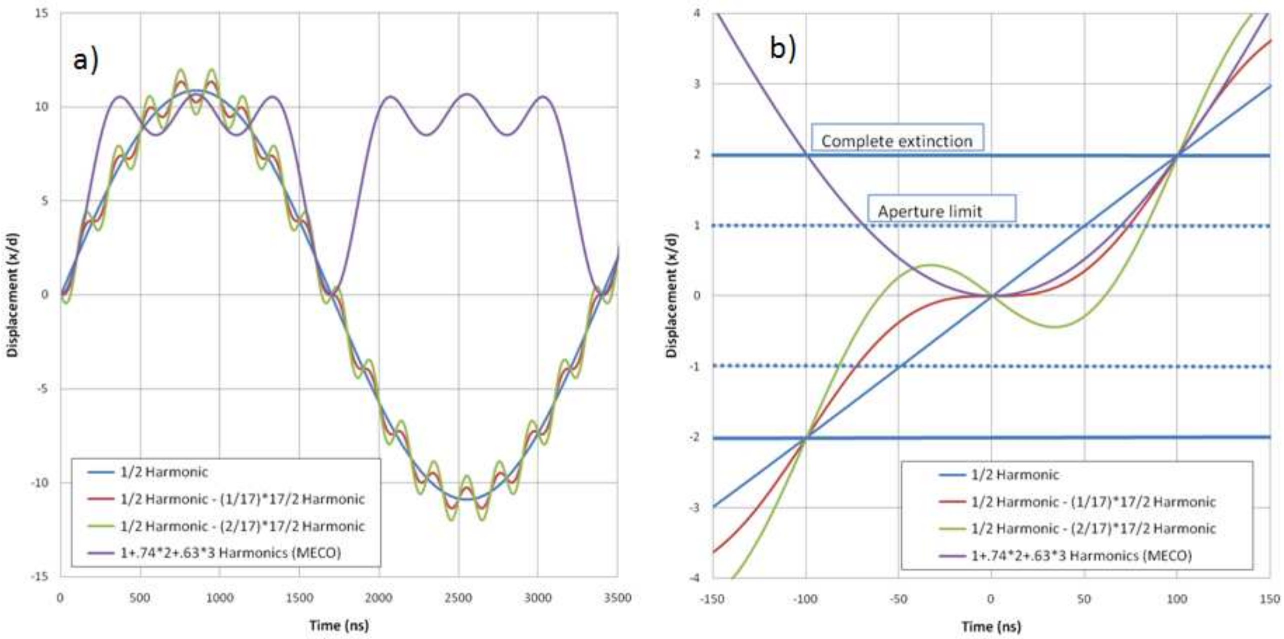

Figure 3: The extinction kicker waveforms which are analyzed in this note. In all cases, amplitudes have been normalized so that complete extinction is achieved at ±100 ns. Figure a) shows the complete waveform over two bunch cycles, while b) shows the detail near the nominal bunch time. The defining aperture is indicated, as is the amplitude corresponding to complete extinction. Note that the MECO waveform has been shifted to put the peak at zero, to facilitate comparison with the other designs.

3 Magnet Specifications

Configuration	**Harmonic Components**					
	kHz	**Max.**	**kHz**	**Max.**	**kHz**	**Max.**
Sine Wave	300	5.44				
Mod. Sine Wave A	300	5.44	5100	.32		
Mod. Sine Wave B	300	5.44	5100	.64		
MECO Design	600	1.64	1200	1.22	1800	1.03

Table 1: Magnitude the individual frequency components in the configurations considered. Scale is relative to the total required bend field, as specified in Figure 2

Table 1 shows the harmonic content for the schemes described above. The magnitudes in the table are the peak integrated bend strengths (Bl) relative to the total bend strength required for extinction, as specified in Eq. 2 for β_x=250 m.

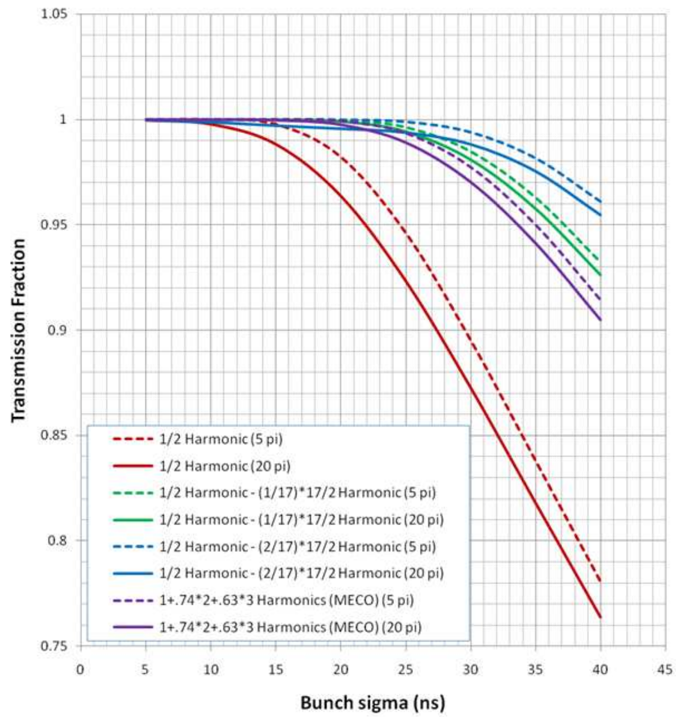

Figure 4: Beam transmission as a function of σ_t for the four extinction kickers. Dashed and solid lines show the results for a 95% normalized emittance (ϵ_{95}) of 5 and 20 π-mm-mr, respectively. Gaussian distributions have been assumed in both the longitudinal and tranverse planes.

Configuration	**Harmonic (kHz)**	**Length (cm)**	**Peak Field (G)**	**Aperture (Bend Plane, cm)**
Sine Wave	300	600	77.9	8.2
Mod. Sine Wave A	300	300	155.9	7.8
	5100	300	9.2	7.3
Mod. Sine Wave B	300	300	155.9	7.9
	5100	300	18.4	7.3
MECO Design	600	200	70.5	7.7
	1200	200	52.4	7.5
	1800	200	44.2	7.3

Table 2: Length, peak field, and bend plane aperture for the individual magnets in the various schemes. In all cases, the gap in the non-bend plane is 1.2 cm, determined by the minimum achievable waist.

Table 2 shows the actual magnetic specifications for the different schemes. In the case of multiple harmonics, we have simply divided the total 6 m length equally amongst the components, although magnet design considerations may lead to a somewhat different allocation of space. The aperture in the bend plane is that required to accommodate the 50 π-mm-mr admittance plus the total lateral deflection. This is under the assumption that no beam, even out of time, should hit the magnet. In the case of multiple harmonics, it's assumed that the highest harmonic comes first, to give it the smallest aperture, although this is a minor effect.

The aperture in the non-bend plane (magnetic gap) should be as small as possible. As was discussed in [1], if we assume suppression of chromatic effects, the smallest aperture through which a beam may be transmitted is

$$g = 2\sqrt{\frac{AL}{\beta\gamma}} \tag{5}$$

In this case, this would give 11.2 mm. We will assume a full gap width of 1.2 cm for all cases.

4 Discussion

The simple, single harmonic in the Mu2e proposal will probably have unacceptable losses for realistic bunch lengths. In addition, the high slew rate the transmission time will probably require a compensating dipole. In the case of the other three schemes, it is likely that the compensating magnet will not be required.

Given the difficulty of designing high frequency magnets, the minor transmission improvement of "Modified Sine Wave B" almost certainly doesn't warrant the doubling of the required field for the 5.1 MHz component.

Therefore, the most promising candidates at the moment appear to be the "Modified Sine Wave A" scheme and the "MECO" scheme, and should be made based on the difficulty of designing the highest frequency magnet. Specifically,

- **Modified Sine Wave A:**

  Frequency: 5.1 MHz

  Peak Field: 9.2 Gauss

  Length: 2 m

- **MECO:**

  Frequency: 1.8 MHz

  Peak Field: 44.2 Gauss

  Length: 2 m

If these turn out to be a similar challenge, then the first scheme has the advantage of requiring only two types of magnet rather than three.

References

[1] E. Prebys, "Optimizing of AC Dipole Parameters for Beam Extinction", http://mu2e-docdb.fnal.gov, Mu2-doc-534-v1

[2] *Carol Johnstone, private communication.*

[3] E. Prebys, "Parametric Analysis of Beam Transmission in the Mu2e Extinction Channel", http://mu2e-docdb.fnal.gov, Mu2-doc-550-v3

[4] Mu2e Collaboration, "Proposal to Search for $\mu N \rightarrow eN$ with a Single Event Sensitivity Below 10^{-16}", FNAL Proposal E-973, http://mu2e-docdb.fnal.gov, Mu2e-doc-388-v1. Sec. 6.5.

[5] W. Molzon, "Proton Beam Extinction", MECO-EXT-05-002 (2005), http://meco.ps.uci.edu/old/ref_design/MECO-EXT-05-001V1.02.pdf